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Chip-scale cold atom and trapped ion experiments can unleash the power of quantum science in the field

Cold atom experiments are among the most powerful and precise ways of investigating and measuring the Universe and exploring the quantum world. By trapping atoms and exploiting their quantum properties, scientists can discover new states of matter, sense even the faintest of signals, take ultra-precise measurements of time and gravity, and conduct quantum sensing and computing experiments.

However, as powerful and sophisticated these experiments are, currently they're still confined to the highly controlled environment of the laboratory, set up on optical tables and racks of equipment designed to isolate the environment and afford users the stability to precisely align the various lasers and optical components — including lenses, modulators, frequency shifters and other components that generate, manipulate and tune light waves needed for quantum experiments.

There's a wealth of knowledge to be gained by taking these experiments out of the laboratory and using their power to measure and monitor phenomena in the outside world, according to UC Santa Barbara electrical and computer engineering professor Daniel Blumenthal.

"You can measure sea level rise, changes in sea ice, even earthquakes with a hundred-kilometer precision," he said. "Literally, events happening on Earth you can

see from the gravitational fields around the planet. Additionally, precise measurements of time in space will open up new avenues of gravitational experiments and search for new particles such as dark matter.”

Small components, big performance

That’s why, for more than an entire decade, Blumenthal and collaborators have been working to translate the various functions of current cold-atom quantum experiments to a more portable, deployable form, integrating entire tabletop systems into devices that can sit in the palm of your hand. It began with a series of chip-scale projects for the U.S. Defense Advanced Research Projects Agency (DARPA).

“They wanted to make a small form-factor atomic clock,” Blumenthal recalled of one particular project, “and we were responsible for beam delivery.” The “beam” refers to the lasers used to trap, cool and probe the timekeeping atoms — likely cesium or rubidium — which have to be confined from their atomic source to a cold “atomic molasses” where the timekeeping can be performed.

That effort led the researchers to ask: Why not miniaturize the rest of the optical table? In addition to beam delivery, there are components responsible for light (lasers), stabilization cavities, optical modulators, frequency shifting, frequency programming, gating and intensity control — all hardware meant to manipulate and modify the optical signal as it is relayed from point to point.

This miniaturization is not a simple task. In addition to replicating the functions of an optical table, the components have to do so with the performance necessary to perform the cooling, trapping, preparation and

measurement of atomic states on miniature chips as would be done on conventional optical tables. These components must also afford users the same stability in the outside world, all in a durable setup that can withstand the extreme environments into which they might be deployed.

“We want to create the same stability and precision, but with the addition of reliability and ease of making more to scale to large numbers of qubits,” Blumenthal explained. The chips would also require less power, he said, and cost less to produce

for wider accessibility and commercialization.

Fortunately, advances in integrated photonics have been making it increasingly possible for engineers and scientists to develop chip-scale optical hardware; in other realms such as telecommunications and biomedicine, photonic integrated circuits are already major players. The time was ripe to ride the wave.

The first major milestone for Blumenthal and his team came in 2023 when they announced that they were able to [create cold rubidium atoms with beams delivered by integrated photonics for the first time](#), via their photonic integrated 3D magneto-optical trap (PICMOT). The beam delivery, embedded into a low-loss silicon nitride integration platform, connects cooling and repumping lasers to three beams that then interface to rubidium atoms in a vacuum. The three beams traverse the atom cell and are reflected by mirrors back on themselves to form the optical intersection region used to cool down and trap rubidium atoms, in combination with magnetic coils. Once the cooled atoms are formed, other lasers can be used to exploit the cold atoms' properties and perform further quantum experiments.

“Warm atoms — thermal atoms — move around a lot,” Blumenthal explained. “If you now cool the atoms and attach a laser to those transitions, you can make a more precise sensor and clock.”

The researchers' proof of concept demonstrated that their tiny PICMOT was able to trap over a million atoms from the rubidium vapor inside the vacuum cell and cool them down to 250 microkelvin (that's about -460°F or -273°C). According to Blumenthal, the more atoms trapped and cooled, the more precise the resulting measurement would be for these neutral atom experiments.

“Colder atoms plus more atoms equals better precision and more sensitivity,” Blumenthal said. “It's because you're averaging the measurement out over more sensors.”

In 2024 Blumenthal's lab reported a further accomplishment: [integration of an ultra-low linewidth, self-injection locked 780nm laser onto a silicon nitride chip](#). Using a common, commercially available Fabry-Pérot laser diode as the light source, the team was able to “clean up,” “calm down” and tune the laser to the desired frequency with photonic components they had been developing, including ultra high-quality factor resonators and lowest-loss waveguides.

In cleaning up the spectral “noise” that comes with the store-bought laser, Blumenthal said, it becomes possible to use the light for quantum applications. The narrow linewidth, he explained, means that the emitted light is in a single frequency and is also stable enough to overcome internal and external noise and vibration.

“Noise and a noisy large linewidth would limit the sensitivity of the sensor, or the speed of the quantum computer, or the stability of the atomic clock,” he said. “A narrow linewidth, low-noise laser comes into play when you want to do the precision work. Other functions, such as cooling don’t require that precision laser, but there are quantum functions that do.”

Indeed, the resulting photonic integrated laser is comparable to the ones in conventional setups, according to Blumenthal Lab member Andrei Isichenko.

“In some ways the performance is improved, compared to conventional lasers

because of full chip-scale integration,” he said. The compact form factor allows for faster feedback, which in turn suppresses noise and leads to a more robust signal. Fiber optics also accumulate fewer random fluctuations relative to their free-space counterpart, adding to the stability of the signal on chip.

Putting it all together

With much of the optical table infrastructure for generating, moving and controlling light miniaturized, it’s only a matter of time before all these tiny 3D MOT components, including the lasers and the reference cavity, are integrated on a single chip. [In an invited article for the journal Optica](#), the researchers draw upon their experience and report on the progress and discuss potential paths toward integration.

“We are there for the photonic engine for neutral atoms,” Blumenthal said, referring to the lasers, optical components and light control and delivery. For systems that are based on trapped ions — atoms with an unequal number of protons and electrons — they are “making their way to that engine.”

As for the “physics package,” which contains the vacuum cell and the atoms to be cooled and trapped, the researchers are still experimenting with how to implement ideal conditions on chip, but they’re getting close, Blumenthal said, explaining that

when it comes to trapping neutral atoms, more is better. But there are other ways to use atoms for these applications that utilize trapped ions, which typically require just a few atoms in a two-dimensional setup. This is another area of intense interest and effort for the Blumenthal group.

“For the trapped ion physics package the trap will be on chip this year,” he said. “We are still a ways off from moving the physics package which holds the neutral atoms on to a chip, and we are collaborating with UMass Amherst on that.” In fact Blumenthal and his collaborator Robert Niffenegger at UMass have utilized [integrated lasers to create quantum qubits with trapped ions for the first time](#).

“The creation of a trapped ion qubit with an integrated laser in the ultra low loss silicon nitride platform is a huge milestone,” Blumenthal said, “that paves the path towards full integration of the trap, lasers, and optics and creation of compact

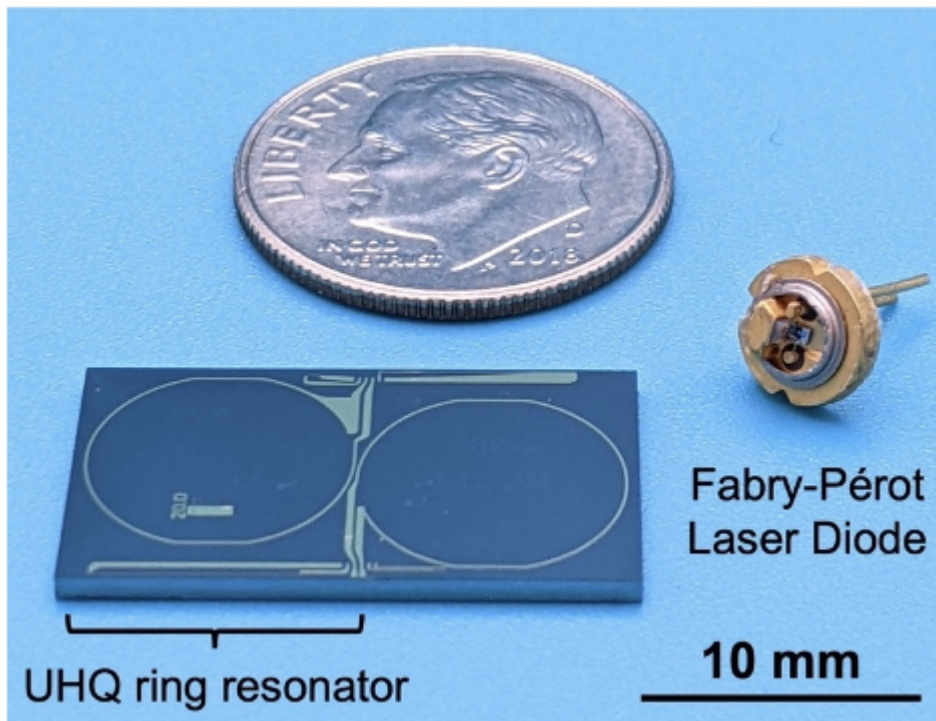


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Scale comparison of 780 nm ultra low linewidth self injection locked laser for rubidium atom compute and sensing. Isichenko, A. et al., Scientific Reports 14(1): 27015 (2024)

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A 493 nm visible blue light silicon nitride piezoelectric modulator for barium atomic quantum computer. Montifiore, N., Isichenko, A., Wang, J., Chauhan, N., Harrington, M., Pushkarsky, M. and Blumenthal, D. (2025). C251. "Integrated Low-Power Blue Light PZT Silicon Nitride Ring Modulator for Atomic and Quantum Applications. Conference on Lasers and Electrooptics (CLEO). Long Beach, CA.

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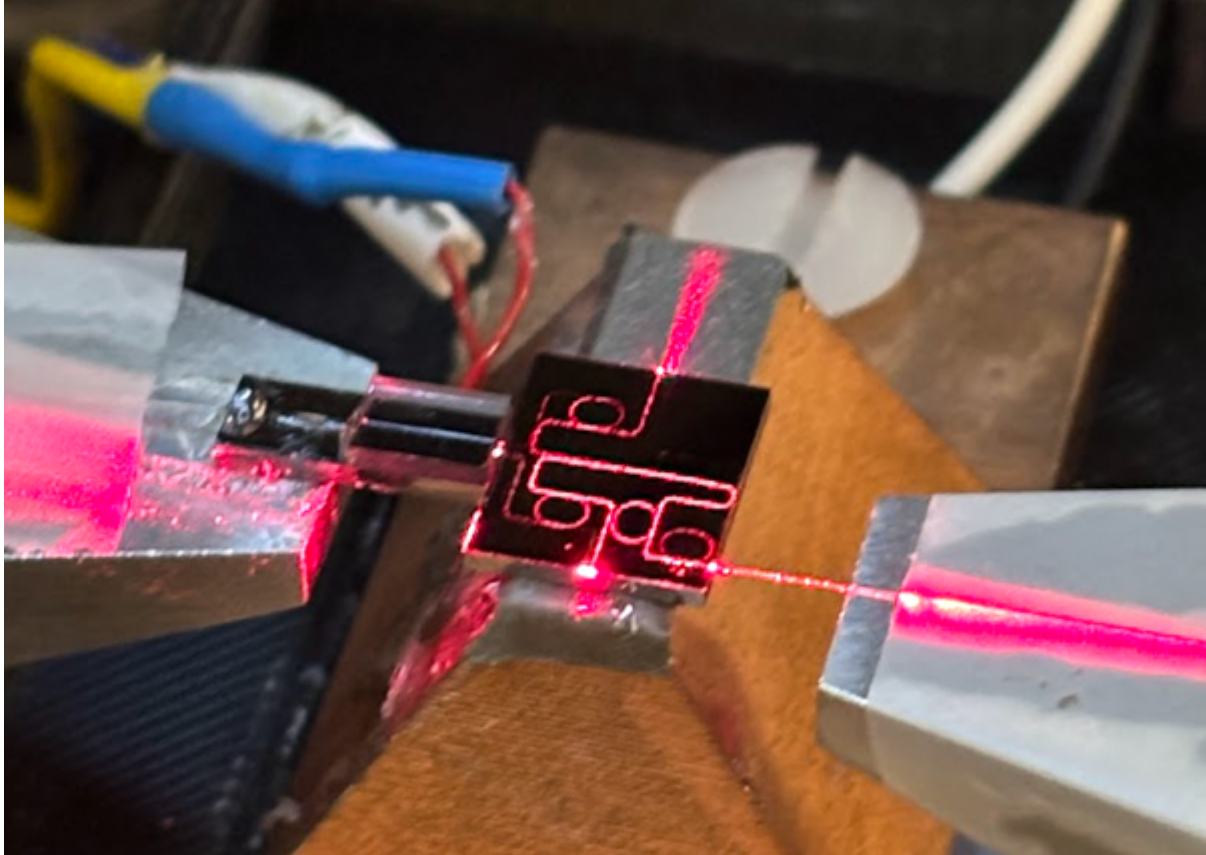


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Photonic integrated lasers for rubidium cold atom quantum compute and sensing

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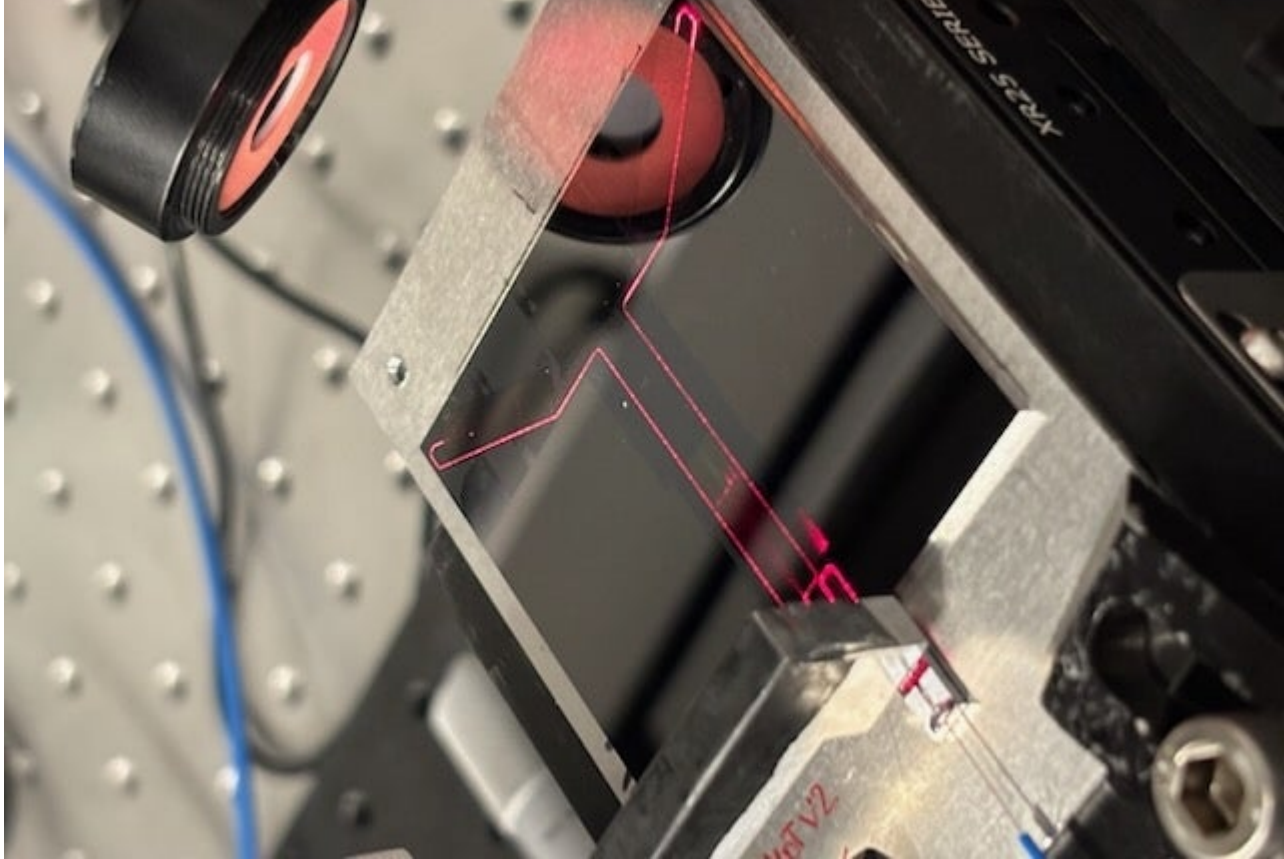


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3D beam delivery to compact cold atom 3DMOT.

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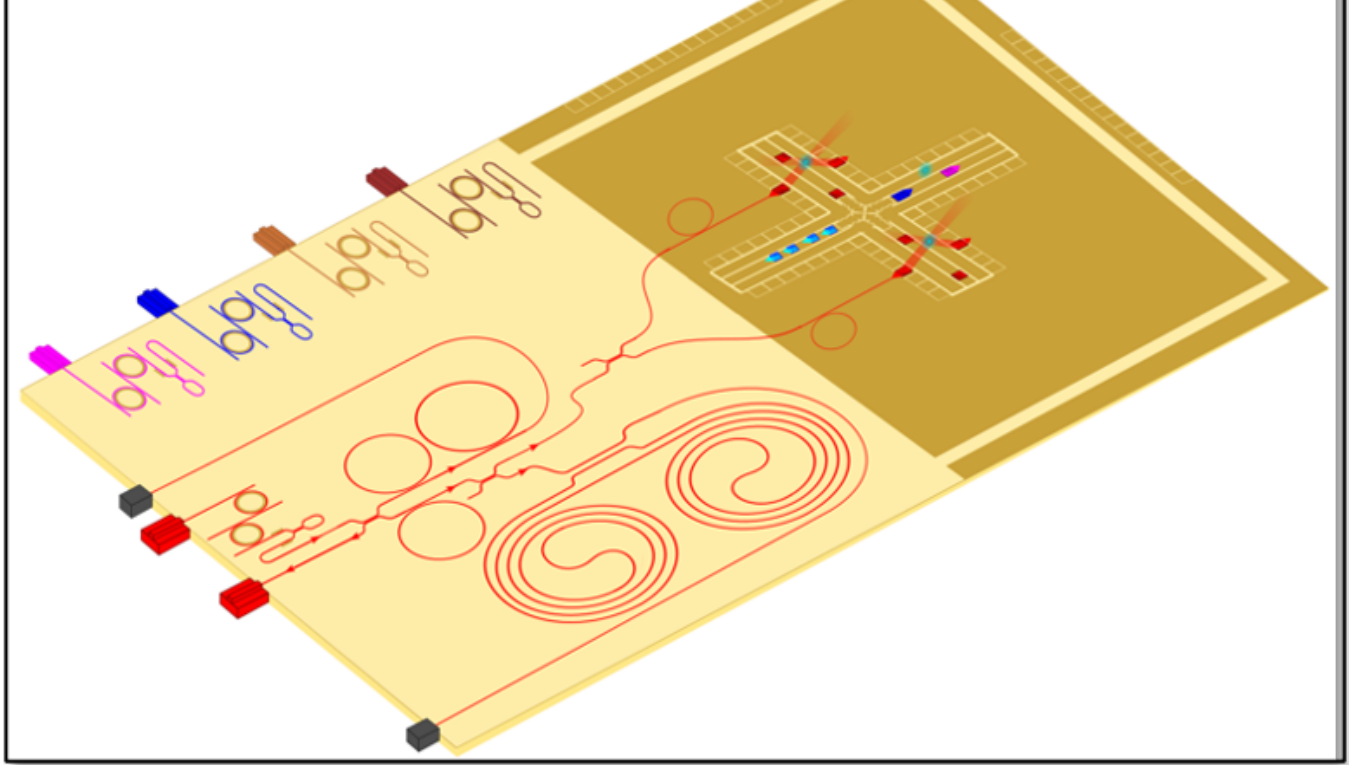


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Illustration of fully integrated trapped ion quantum compute and sensing. Chauhan, N., Caron, C., Wang, J., Isichenko, A., Helaly, N., Liu, K., Niffenegger, R. J. and Blumenthal, D. J. (2024). Trapped ion qubit and clock operations with a visible wavelength photonic coil resonator stabilized integrated Brillouin laser, ArXiv. arXiv:2402.16742v1.

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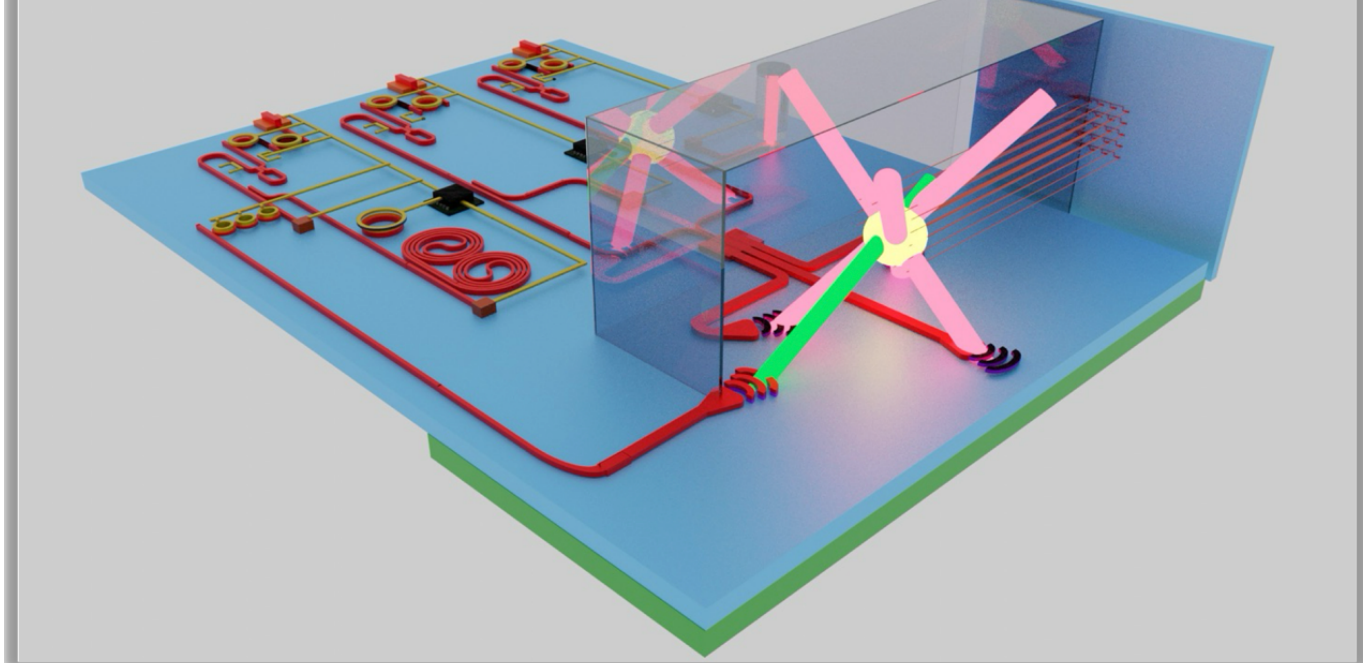


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Illustration of a future fully integrated 3D-MOT with integration of optical tweezer array to trap and manipulate individual cold atoms for quantum compute and sensing

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